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DISPERSION OF JETTISONED JP-4 JET FUEL BY ATMOSPHERIC TURBULENCE, EVAPORATION, AND VARYING RATES OF FALL OF FUEL DROPLETS

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SUMMARY

Techniques whereby the combined effects of dispersion of jettisoned jet fuel by atmospheric turbulence, evaporation from fuel droplets, and varying rates of fall of the droplets may be approximately calculated are presented. Fall and evaporation of such droplets in a quiet atmosphere were considered in a report on that aspect of the problem (NASA TN D-33).

The calculation techniques evolved were applied to the problem of fuel-air-ratio prediction in the case of jettisoning from an aircraft traveling at a low speed (250 knots) at small ground clearances (up to 1000 ft). The predictions were made for a warm (21° C), windy day; a warm, quiet day; a cold (-39°), windy day; and a cold, quiet day.

For jettisoning rates (in lb/(ft of aircraft travel)) which approach maximum values expected for current jet transports, the fuel-air ratios calculated were found to be, in general, much less than the lean flammability limit for jet fuels in air (0.035). In addition, permissible jettisoning rates, such that the allowable fuel-air ratio (0.035) would occur, are indicated; it is shown that even for jettisoning from very low altitudes this ratio would not be exceeded for jettisoning rates many times as great as those now contemplated.

It is concluded that jettisoning at rates expected for current jet transports will be permissible at ground clearances above 500 feet under virtually all atmospheric conditions if the sole criterion is that of possible establishment of a fire-hazardous condition between aircraft and ground. The possibility of establishment of such a condition on the ground as the result of accumulation of both liquid and vaporized fuel was not considered, but may well be of importance.

INTRODUCTION

It is occasionally necessary to jettison all or a major fraction of the fuel load of an aircraft. It is therefore desirable that it be possible to estimate beforehand the concentrations of liquid and of vaporized fuel at any given point in the atmosphere at a given time after initiation of jettisoning. Such calculations would enable ground-contamination and combustible-mixture hazard predictions to be made on a quantitative basis.

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As is indicated in a companion report (ref. 1), a general solution would take into account many factors. Among them are the motion of the craft during jettisoning, the details of the dispersion process in the vicinity of the exit nozzles or chutes, the effect of vehicle wake, the mean state of the atmosphere in the area, and atmospheric turbulence. A factor not mentioned in this list is treated in some detail in reference 1, namely, the behavior of fuel droplets falling with or without evaporation in a quiet atmosphere. In that reference, results are given concerning the fall of JP-4 fuel droplets having diameters ranging from 250 to 2000 microns from starting altitudes up to 7000 feet for sea-level temperatures varying from -30° to $+30^{\circ}$ C.

In the present report a more complete treatment of the general problem is undertaken. The additional dispersing effects of atmospheric turbulence and of vertical separation as caused by varying rates of fall are treated in an approximate manner. Liquid-fuel-concentration estimates are then made for a small number of simple low-altitude jettisoning situations by considering the combined effects of mechanical dispersion and droplet evaporation.

In the present treatment, no attempt is made to consider in any way the details of what might be called "early" dispersal phenomena, that is, the events of the first second or two after release of a given incremental volume of fuel from the aircraft. A considerable body of experimental data must be accumulated before this becomes feasible. Rather, the assumption is made that within a very short time after release a concentrated wake, or plume, of fuel droplets of varying size is present behind the aircraft and at essentially the original aircraft altitude. Thus, downwash and aircraft-generated turbulence effects are ignored.

The plume, once formed, will sink toward the ground and spread both horizontally and vertically. The approximate details of this spreading process, and the combining of these effects with those having to do with the evaporative loss of mass of the individual droplets (and, hence, of the plume) are the subjects of this treatment.

In general, jettisoned fuel leaves jet transports through two orifices or from two chutes rather than through (or from) one. In at least one case, the two departure points are separated by nearly the full wingspan from each other. In such a situation, the present treatment could be considered as applying to either plume rather than to a single, combined plume; the rate of fuel flow would, of course, be adjusted accordingly.

Though there would appear to be a distinct possibility that ground contamination is of importance, from the point of view of creation of both nuisances and fire-hazardous conditions, that aspect was not considered in this study.

ANALYSIS

The fall of jet fuel droplets through a quiet atmosphere with or without evaporation is treated in reference 1 and need not, as such, be treated here. In this section, three subjects are considered, namely: (1) vertical dispersion as a result of varying rates of fall of the droplets, (2) horizontal and vertical dispersion as caused by atmospheric turbulence, and (3) approximate means of combining these two effects with fall histories of droplets in a quiet atmosphere. Included with the last are remarks concerning numerical values used in the (largely exemplary) calculations.

Vertical Dispersion as Result of Varying Rates of Fall

It is indicated in reference 1 that at low altitudes (below 10,000 ft) terminal falling speeds of droplets of approximately fixed densities may be regarded as a function of droplet diameter only. The exact relation is given in reference 1 and is not relevant here.

In this treatment, it is assumed that no droplet affects another droplet in any way. Let an idealized circular cross section of a fuel droplet plume be considered (fig. 1). Initially, fuel droplets of all sizes are homogeneously distributed over such a cross section. Disregarding all other effects, this cross section would descend toward the ground and at the same time distend in a vertical direction as the result of the large spread (0 to 20 ft/sec) in fall speeds of droplets of varying sizes. After a moderately long time, the smallest droplets would be found at small distances below their original levels, whereas the largest would be much closer to the ground. Figure 1(c) illustrates this situation.

The liquid volume concentration would attain a maximum (less than the original) at some point in the pattern, and there will be a particular droplet diameter such that droplets of that diameter are, roughly, symmetrically distributed about that point. In the following discussion, the term "center" is used to denote the point of highest volume concentration, and the term "medial" is arbitrarily used to designate those droplets which are symmetrically distributed about such a center. The dimensions of the plume cross section are as follows: major axis, $2r_c + \Delta H$; minor axis, $2r_c$; where r_c is the original radius of the idealized cross section and ΔH is the difference in distances of fall between largest and smallest droplets. If ΔH is less than or equal to $2r_c$ (fig. 1(b)), the concentration at the pattern center is not less than the original value since droplets of all sizes are still present at that level at the original concentrations.

However, for all values of ΔH greater than $2r_c$ (fig. 1(c)), a reduction in concentration does occur. The largest droplets now occupy a circular cross section, the highest point of which now lies below the bottom of the cross section occupied by the smallest droplets. Between these two circles, a region exists in which droplets of extreme sizes are absent, as mentioned previously.

At a given time after release (θ), only those droplets will be present near the center of the pattern which neither upward nor downward motion relative to the center has displaced more than 1 radius (r_c). Accordingly, droplets within two limiting sizes will still be found at the center: droplets having diameters smaller than those of medial size by the quantity $\Delta D = \dfrac{r_c}{\theta\left(\dfrac{dU}{dD}\right)_{medial}}$, and droplets having diameters in excess of those of medial size by the same increment (an average value of dU/dD being adopted for a small diameter range). (Symbols are defined in appendix A.)

It follows that only droplets falling within the diameter limits $D_{medial} \pm \dfrac{r_c}{\theta\left(\dfrac{dU}{dD}\right)_{medial}}$ will contribute to the concentration at the level in question. (In general, dU/dD will not be constant over any finite diameter range, but the generalization valid in this situation is easily made.) Accordingly, the factor by which the original concentration is reduced solely through vertical-fall dispersion is the ratio of the volume of all droplets within the indicated diameter limits (per unit volume of air) to the original volume of all droplets released.

Extension of this simple approach to noncircular patterns can be made in an obvious manner: half of the vertical dimension of the original pattern at a given point becomes the variable in the numerator of the final expression (rather than r_c).

Horizontal and Vertical Dispersion Caused by Atmospheric Turbulence

The statistical nature of the fluctuations of air motion that occur in the atmosphere is compatible only with mathematical descriptions reflecting, to a reasonable degree, this statistical behavior.

A fairly thorough review of atmospheric diffusion theories is presented in chapter 4 of reference 2. In particular, the problem of the selection of proper values of diffusion coefficients is discussed in some detail.

Two expressions of significance in the present study are now given. A basic diffusion equation (ref. 2) is the following:

$$\chi(x,y,z,\theta) = \frac{Q}{(4\pi\theta)^{3/2}(K_xK_yK_z)^{1/2}}\, e^{-\frac{1}{4\theta}\left(\frac{x^2}{K_x}+\frac{y^2}{K_y}+\frac{z^2}{K_z}\right)} \tag{1}$$

in which χ is the concentration distribution due to the instantaneous release at time $\theta = 0$ of a mass Q of material at the origin of the coordinate system; x, y, and z are distances measured along axes of that coordinate system (which moves with the mean wind); and K_x, K_y, and K_z are the respective diffusion coefficients (assumed constant) along the respective axes.

Equation (1) is simply a solution of the diffusion differential equation (ref. 2, p. 38) for the case in which K_x, K_y, and K_z are constants.

On the basis of a statistical approach, O. G. Sutton (ref. 2, pp. 44-45) arrived at a treatment which takes into account in some measure both the tendency of the effective diffusion coefficient to increase with time and the variation in wind speed and turbulence in the lower levels of the atmosphere.

Sutton's expression, which, when properly used, describes more precisely the situation for which equation (1) is a rough solution, is the following:

$$\chi = \frac{Q}{\pi^{3/2}\; C_xC_yC_z(\overline{u}\theta)^{3(2-n)/2}}\, e^{-(\overline{u}\theta)^{n-2}\left(\frac{x^2}{C_x^2}+\frac{y^2}{C_y^2}+\frac{z^2}{C_z^2}\right)} \tag{2}$$

In this equation, C_x, C_y, and C_z are "virtual diffusion coefficients" for the spreading directions x, y, and z, respectively, while $\bar{u}$ is the mean wind speed at the altitude in question. Further, n is a stability parameter; mean wind speed varies with altitude in accordance with the expression $\bar{u} = \bar{u}_1(z/z_1)^{n/(2-n)}$.

If a comparison of equations (1) and (2) is made, it will appear that they are identical when

$$\left.\begin{aligned} K_x &= \frac{C_x^2}{4}\,\bar{u}^{(2-n)}\theta^{1-n} \\ K_y &= \frac{C_y^2}{4}\,\bar{u}^{(2-n)}\theta^{1-n} \\ K_z &= \frac{C_z^2}{4}\,\bar{u}^{(2-n)}\theta^{1-n} \end{aligned}\right\} \tag{3}$$

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If C_x, C_y, and C_z were themselves known constants, in many simple meteorological situations (implying absence of nearby fronts or other discontinuities) it would merely be necessary to select the proper value of n and perform the calculations. As might be anticipated, this is not possible. In actuality, C_x, C_y, and C_z, while not time-dependent if the meteorological situation is essentially fixed, are found (both theoretically and experimentally) to vary both with the turbulence index n and with altitude. In addition, C_y and C_z are theoretically related to the transverse airspeed fluctuations in the y- and z-directions - which have not received sufficient experimental attention.

A further difficulty is that effective diffusion coefficients will vary with the density and configuration of the particles under consideration (ref. 3, e.g.). This point is discussed briefly in appendix B; it is indicated there that, if air-motion fluctuations at relatively high frequencies are considered, the suspended particles will not "follow" the motions of the air perfectly. Thus, differences in diffusion coefficients arising from differences in the densities and shapes of the particles may not generally be ignored where meteorological situations are concerned, but in this work this has had to be done.

When atmospheric turbulence is reasonably isotropic (which is, however, frequently not the case within the first 2000 ft), $C_x = C_y = C_z$ and the values of C^2 may be approximated in many situations simply by selecting values from curves such as those of figure 2. The two curves of the figure indicate the values of C^2 as a function of altitude in meters for two values of n, namely, 0.5 and 0.2. The value 0.5 corresponds to rather stable conditions (small lapse rates), whereas the value 0.2 corresponds to moderately unstable conditions (large lapse rates). These curves are faired and extrapolated plots of the data of page 53 of reference 2 with some allowance (in the extrapolated portions) for the somewhat higher values given elsewhere (ref. 2, p. 105, e.g.).

It will be noted that the values of C^2 for the stable conditions are, very closely, about 0.1 of those for the unstable; this trend was used to extrapolate the $n = 0.5$ values to altitudes above 150 meters.

The problem remains of taking into account the frequent anisotropy of the turbulence of the ground layer of the atmosphere; consideration of this difficulty is, however, deferred; a modification of equations (1) and (2) is first discussed.

The actual source in the case of an aircraft more nearly approximates an instantaneous line source than an instantaneous point source. It is therefore desirable to integrate expressions such as equations (1) and (2) to obtain the corresponding expressions for such a source. Strictly, the variations of K in the direction of flight should be taken into account. However, within the framework of a crude attack on the problem, such variations may be ignored. Equation (1) is used; the integral is then

$$\chi = \int_{-\infty}^{+\infty} \frac{Q^*}{(4\pi\theta)^{3/2}(K_x K_y K_z)^{1/2}} e^{-\frac{1}{4\theta}\left[\frac{(x-x_1)^2}{K_x} + \frac{(y-y_1)^2}{K_y} + \frac{(z-z_1)^2}{K_z}\right]} dx_1$$

where Q^* is the mass of material released per unit distance and χ is the concentration at a point x,y,z due to an instantaneous line source extending from minus infinity to plus infinity along the x-axis. The result of the indicated integration is the following when K_x is assumed invariant with x_r:

$$\chi = \frac{Q^*}{4\pi\theta(K_y K_z)^{1/2}} e^{-\frac{1}{4\theta}\left[\frac{(y-y_r)^2}{K_y} + \frac{(z-z_r)^2}{K_z}\right]} \tag{4}$$

(An isotropic version of this is given as eq. (4.37) of ref. 4.)

In subsequent discussion, the y-axis is considered to be oriented in the horizontal direction, while the z-axis is considered to be vertical.

The concentration along the x-axis, which is the region of principal significance, is then simply

$$\chi_a = \frac{Q^*}{4\pi\theta(K_y K_z)^{1/2}} \tag{5}$$

An approximate procedure was used whereby the solution of equation (5) was rather arbitrarily adopted, but χ_a at any given time was calculated on a step basis. In this method, initial values of K_y and K_z (calculated on the basis of eq. (3)) were taken as fixed for a reasonable (short) period. The ratio χ_a/Q^* was calculated using the elapsed time θ and the selected values of K_y and K_z.

The values K_y and K_z were then evaluated for the second interval $(\Delta\theta)$ and the product $(K_y K_z)^{1/2}\Delta\theta$ was formed and added to the first such product to form what in effect was the rough integral $\int_0^\theta (K_y K_z)^{1/2}\, d\theta$ for the total elapsed time θ. The ratio χ_a/Q^* was again calculated using this effective integral. The process was repeated for each successive interval; in effect, the integral $\int_0^\theta (K_y K_z)^{1/2} d\theta$ was used as the independent variable instead of θ itself.

One justification of this technique is the following: Let it be supposed that K_y and K_z may be taken as constant over an interval, say θ_1. Then, at any time during the interval $0 \leq \theta \leq \theta_1$, the axial concentration will be given by

$$\chi_a = \frac{Q^*}{4\pi\theta(K_y K_z)_1^{1/2}}$$

It is simpler to consider the matter in terms of the specific volume χ^{-1}. Thus,

$$\chi_a^{-1} = \frac{4\pi(K_y K_z)_1^{1/2}}{Q^*}\,\theta$$

The growth of χ^{-1} during this initial period is indicated as the first leg of the broken line of figure 3. The slope of the line is $4\pi(K_y K_z)_1^{1/2}/Q^*$. If, now, at time θ_1 a sudden change of $K_y K_z$ to a

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second value occurs, the slope changes accordingly and the rate of growth of χ_a^{-1} is then $4\pi(K_yK_z)_2^{1/2}/Q^*$. Accordingly, during the second interval, $\theta_1 < \theta \leq \theta_2$,

$$\chi_a^{-1} = \chi_{a,1}^{-1} + \frac{4\pi}{Q^*}(K_yK_z)_2^{1/2}(\theta - \theta_1)$$

$$= \frac{4\pi}{Q^*}\left[(K_yK_z)_1^{1/2}\,\theta_1 + (K_yK_z)_2^{1/2}(\theta - \theta_1)\right]$$

The generalization to the case of continuous variation of K_yK_z follows in accordance with the elementary calculus

$$Q^*\chi_a^{-1} = 4\pi\int_0^{\theta}(K_yK_z)^{1/2}\,d\theta \qquad (6)$$

While it is true that in numerical work the values of the coefficients C (or C_y or C_z), and hence K (or K_y or K_z), may not be known a priori as a function of time because experimental results are presented in terms of altitude (and stability index), altitudes of course become available as a calculation proceeds, and therefore the diffusion coefficients may be evaluated as though they were functions of time alone.

The manner in which anisotropy was taken into account is now discussed: In the case of the calculations made in connection with a "gusty" meteorological situation, it was considered that anisotropy, if present, was of negligible consequence. Accordingly, K_y and K_z, as well as C_y and C_z, were taken as equal.

In the case of the "quiet day" calculations, however, an attempt was made to obtain from the literature estimates of the ratio K_y/K_z for typical inversion situations. It was concluded that a representative, "order-of-magnitude" value would be 10.

In both situations, the product $(K_yK_z)^{1/2}$ was required to equal the value $(C^2/4)\bar{u}^{(2-n)}\theta^{1-n}$ at any given time. Thus, the value of K_y in the quiet-air case was assumed to equal $(\sqrt{10}/4)C^2\bar{u}^{(2-n)}\theta^{1-n}$, while K_z was assumed to equal $C^2(4\sqrt{10})^{-1}\bar{u}^{(2-n)}\theta^{1-n}$. Additional details are mentioned in the following section.

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Approximate Calculations

Calculations - approximate or otherwise - which take into account droplet evaporation and vertical-fall dispersion caused by atmospheric turbulence imply a knowledge of the droplet size distribution. In the absence of such knowledge, a size (or, equivalently, a volume) distribution must be assumed. Information of three kinds is available: (1) the maximum (stable) droplet diameter is about 2000 microns (ref. 5); (2) because special atomization devices are not used during jettisoning, volume contributions at diameters below the diameter at which the peak contribution occurs must fall off sharply; and (3) the "mean droplet size" (the meaning of which is discussed later) at an airspeed of 250 knots is in the vicinity of 180 microns. The latter figure is an estimate based on the work of Merrington and Richardson (ref. 6). They observed circular blots of dye on absorptive paper placed on the ground below a low-flying aircraft from which various dyed liquids were emitted in the form of a jet. Their conclusion was that only relative airspeed (as between fluid and air) and fluid properties were of significance, and they arrived at the empirical relation $V\bar{D} = 500\ \nu^{0.2}$, where V is the fluid-air relative speed in centimeters per second, $\bar{D}$ is the "mean droplet size" in centimeters, and ν is the kinematic viscosity in poises per gram-centimeter^{-3}.

"Mean droplet size" in reference 6 was that droplet diameter at which the peak contribution to total liquid volume occurred. In the present work, the mean size in this rather special sense was taken as 250 microns instead of the 180-micron figure (obtained from $V\bar{D} = 500\ \nu^{0.2}$) for the purpose of introducing a reasonable margin for error. In addition, the volume-mean diameter of 500 microns was assumed; this choice was in large measure dictated by the considerations previously mentioned.

The resulting volume distribution then became that shown in figure 4. It is obvious that this distribution is a rather arbitrary one, but the work of Merrington and Richardson at least ensures its qualitative correctness.

The dispersion calculations that were made were of a preliminary nature and were executed manually. Consequently, only a relatively small number of rough computations were completed. Under such circumstances, the dispersion calculations were limited to that (original) droplet size which would, it was felt, make a maximum contribution to liquid-fuel concentrations under typical circumstances.

In the absence of evaporation, it happens that this droplet size would be (to a first approximation) the volume-mean itself, namely, 500 microns. This fact is the result of two circumstances: The smaller droplets fall much more slowly and are subject during long periods to turbulent dispersal, and larger droplets become widely separated as the result of fall-rate differences. Moreover, there are, in any case, relatively few large droplets.

Frequently, little or no evaporation actually occurs. In reference 1, it is indicated, for example, that only 10 percent of the mass of a droplet of JP-4 fuel having an initial diameter of 500 microns is lost during a fall of 500 feet from an altitude of 5000 feet when the sea-level temperature is -30° C. Approximately as much would be lost during a fall to the ground (sea-level) from an altitude of 500 feet when the sea-level temperature is -39° C (-38.2° F). (The assumed standard change of air temperature was about 9° C in 4500 ft.)

When sea-level temperatures are -9° C (15.8° F) and 21° C (69.9° F), however, the respective estimated mass losses for falls from 500 feet to the ground are about 37.5 and 84 percent. In the case of the JP-4 droplet having an original diameter of 1000 microns, the respective losses for sea-level temperatures of -39°, -9°, and 21° C for falls of 500 feet to sea level are 2.5, 25, and 52 percent. Accordingly, the distribution of volume among droplets of varying sizes will not be seriously affected by evaporation at low temperatures (save for early disappearance of droplets having diameters less than about 150 microns), will be affected significantly but not markedly at temperatures in the vicinity of 0° C, but will be markedly affected at temperatures above about 15° C. Nevertheless, in view of the uncertainty as to the actual droplet volume distribution, the decision was made to base all dispersion estimates on the behavior of droplets having diameters in the vicinity of 500 microns; it is clear that this procedure weights too lightly the contributions of larger droplets when air temperatures are high.

Calculations were made for four different meteorological situations: a cold (sea-level temperature, -39° C), quiet day; a cold, gusty day; a warm (21° C), quiet day; and a warm, gusty day. For the quiet day, a wind of about 4 miles an hour invariable with altitude was assumed. For the gusty day, a wind speed varying with altitude in accordance with the dashed curve of page 22 of reference 2, but having a value of about 22 miles per hour at 1000 feet, was assumed. The sea-level temperatures selected were limited to those for which fall and evaporation results were available (ref. 1). Those had been selected, in part, on the basis of preliminary calculations indicating that very little evaporation of JP-4 occurs at sea-level temperatures below -30° C. At the other end of the temperature range, sea-level temperatures of +30° C, while frequently exceeded in the United States, are more typical of hot-weather conditions than are higher ones. Thus, evaporation rates associated with higher temperatures would occur comparatively rarely. Similarly, the 22-mile-per-hour wind speed is typical of a moderately windy day rather than a rarer, but frequently occurring, very windy one.

The sea-level temperatures of -39° and 21° C were selected so that fall-with-evaporation results for an initial altitude of 5000 feet and sea-level temperatures of -30° and 30° C presented in reference 1 could be used.

The calculations were performed on a time-step basis. Initial steps were 1 or 2 seconds in duration; subsequent steps increased to maximum values of 50 seconds. Assuming a starting altitude of 1000 feet, the altitude at each elapsed time was obtained by using distances of fall of reference 1 in the case of fall from a 5000-foot altitude of a 500-micron droplet.

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At each such altitude, the value of C^2 was obtained from figure 2; the value of n was taken as 0.2 for the gusty-day calculations, while a value of 0.5 was used (ref. 2, p. 53) for the quiet-day calculations.

At each step, the value of K was then calculated using equation (3); at this point no distinction was made among C_x, C_y, or C_z or among K_x, K_y, or K_z. The value of the integral $1\Big/\left(4\pi\int_0^{\theta} K\,d\theta\right)$ was crudely evaluated at each step by simply adding the successive products $K\Delta\theta$.

In the case of the gusty-day calculations, it was assumed at this point that $K_y = K_z$. An appropriately simplified version of equation (4) is then

$$\chi Q*^{-1} = \frac{1}{4\pi K\theta}\, e^{-r^2/4K\theta} \tag{7}$$

in which r^2 replaces $(y - y_r)^2 + (z - z_r)^2$.

The value $r = 2.536\sqrt{K\theta}$ was then selected so that roughly 90 percent of all droplets of a given diameter, and which are assumed to have been liberated along the original axis, will lie within a circle having r as a radius and a center coincident with the instantaneous center of gravity of the droplets in question. The value r was calculated at each step in the turbulent-air situation.

In the case of the quiet-day calculations, it was assumed (as stated previously) that $K = (K_yK_z)^{1/2}$ and $K_y = 10K_z$. Accordingly, $K_z = K/\sqrt{10}$, and in order that $e^{-z^2\sqrt{10}/4K\theta} = 0.2$, it was necessary that $z = 1.426\sqrt{K\theta}$. Roughly 90 percent of all droplets will lie within a diffusion ellipse, the semiminor axis of which equals that value of z. Accordingly, $z = 1.426\sqrt{K\theta}$ was calculated at each step in the quiet-air situation.

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The major assumption was made that the central fuel concentration (mass per unit volume of air) could then be considered to be the product of four factors, namely: (1) the number of units of mass of fuel released per unit of flight distance; (2) the residual mass fraction for the distance of fall, original droplet diameter, and sea-level temperature in question; (3) the ratio χ/Q^* at the center of gravity as given by equation (6) (taking $(K_y K_z)^{1/2} = K$); (4) a vertical dispersion concentration-reduction factor computed as indicated in the previous section of this report, use being made of the expression

$$\text{Diameter limits} = D_{medial} \pm r_c \Big/ \theta\left(\frac{dU}{dD}\right).$$

In the latter expression, r_c is taken as equaling either r (in the turbulent-atmosphere case) or z (in the quiet-atmosphere case). (The denominator $\theta(dU/dD)$ was evaluated graphically from the appropriate (500-micron) distance-of-fall against time curves of ref. 1.)

A principal physical assumption underlying this procedure is that droplets of a given size will be subject to the same turbulent diffusion while falling, more or less as a group, as that to which they would be if they did not fall, assuming that in the latter case K would vary with time in the same manner.

Fuel concentrations were based on a fuel release rate of 0.24 pound per foot. This release rate is typical of the maximum jettisoning rate expected for existing aircraft at comparatively low airspeeds. Sea-level air density was used in the calculation of fuel-air ratios.

RESULTS AND DISCUSSION

The results are displayed in figures 5 and 6. In the first of these, the predicted fuel-air ratios for the four meteorological situations previously discussed are given as a function of altitude above sea level assuming jettisoning of JP-4 fuel at the 1000-foot level at a rate of 240 pounds of fuel per 1000 feet of aircraft travel.

The large effects of both evaporation and turbulent diffusion are evident. Even in the absence of evaporation and at low turbulence levels, however, it is clear that very low fuel-air ratios would exist after falls of the order of 1000 feet. For example, a fuel-air ratio of about 0.0001 would be reached after a fall of 800 feet in a quiet atmosphere at low temperatures. The principal cause of such high rates of decrease in fuel-air ratio under all conditions is the vertical dispersion associated with variable speeds of fall of the droplets. Curiously, however, this effect is greatest when turbulence effects are small; this is easily seen when it is considered that in the case of extremely large diffusion rates the effective dimensions of diffusion cross sections would be comparable to distances of fall.

The determination of flammability hazards implies a knowledge of lean flammability limits for fuel clouds similar to the fuel plumes under discussion. No experimental data are available concerning such limits. For sprays consisting of droplets smaller than those typical of fuel plumes, however, a few experimental data are available; they indicate that a lean flammability limit for a mixture of fuel and air will remain essentially fixed whether the fuel is in vapor form or liquid droplet form or some combination for a fixed over-all fuel-air ratio. Accordingly, the generally accepted fuel-air ratio of 0.035 was adopted as the lean flammability limit for jet fuels. If a change with percent liquid fuel does occur, the lean limit expressed as a fuel-air ratio will tend to be larger for higher liquid contents, so that the adopted figure is a conservative (safe) one. Finally, the lean limit tends to be independent of altitude for a wide range of altitudes.

In figure 6, safe fuel jettisoning rates are indicated for the four meteorological situations previously discussed. The ordinate is "ground clearance" rather than "altitude" or "distance of fall"; this implies that for every point a different starting altitude was selected such that for that altitude a ground concentration of 0.035 would be reached at the corresponding jettisoning rate indicated along the abscissa scale. Although the curves are plotted as though the calculations were made in that manner, the points were actually estimated from the computation results exhibited in figure 5. For each point, a jettisoning rate was calculated such that a fuel-air ratio of 0.035 was reached after a fall from a fixed 1000-foot altitude to an altitude of 1000 feet minus the corresponding ordinate of figure 6. This is clearly not rigorously correct, but the principal error consists only of an effective deviation of wind speeds from those on which figure 5 is predicated.

Figure 6 indicates that at an expected current maximum jettisoning rate of 100 pounds per second (or 240 lb/1000 ft at 250 knots) ground clearances of less than 100 feet are allowable under the most favorable conditions, that is, in warm, windy weather. However, even under the least favorable conditions, that is, on a quiet, cold day, the ground clearances indicated are very modest. At jettisoning rates as high as 4200 pounds per second, or 10,000 pounds per 1000 feet at 250 knots, ground clearances of only 300 feet would be required even under such unfavorable conditions.

Predictions of this kind are subject to Nature's whims. Random air motions near the ground decrease the dependability of calculations to such an extent that predictions involving clearances of less than perhaps 200 feet are not reliable; the uncertainty is increased by the neglect of downwash effects and other "early" dispersal phenomena occurring in the vicinity of the aircraft.

Nevertheless, most of the jettisoning rates appearing in figure 6 are much higher than any now contemplated, and it appears to be safe to indicate that jettisoning at rates expected for current jet transports will be permissible at ground clearances above 500 feet under virtually all atmospheric conditions. It is emphasized that the sole criterion applied herein was flammability of a fuel-air mixture; ground contamination was not considered, nor was evaporation from possible ground accumulations of fuel.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, July 27, 1959

APPENDIX A

SYMBOLS

C	Sutton's generalized diffusion coefficient in isotropic case (ref. 2)
C_x, C_y, C_z	C for direction indicated by subscript
D	droplet diameter
H	altitude
K	diffusion coefficient in isotropic case
K_x, K_y, K_z	K for direction indicated by subscript
n	stability index
Q	mass of matter released (at a point)
$Q*$	mass of matter released per unit distance
r	radial distance from effective center of distribution
r_c	radial distance to prescribed concentration
U	droplet falling speed (assumed terminal in this study)
u	wind speed
V	relative fuel-air speed (irrespective of direction)
x	coordinate (generally, in axial direction)
y	coordinate (generally, horizontal and at right angles to axis)
z	coordinate (generally, vertical) or vertical distance from center of distribution to prescribed concentration
θ	time
ν	kinematic viscosity of air
χ	matter concentration (mass per unit volume)

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Subscripts:

a	axial
c	at specified concentration
r	reference or origin
x,y,z	along respective coordinate directions
1,2	specified (or particular)

Superscript:

—	mean value

APPENDIX B

EFFECT OF PARTICLE DENSITY ON RESPONSE TO FLUID TURBULENCE

In reference 3, a function $\psi(\omega)$, where ω is the angular frequency characterizing a fluid disturbance, is defined as the ratio of the motional response of a particle to the excitation consisting of the motion of the ambient fluid at the frequency in question. It is further proved that ψ tends to equal unity whenever a drag/inertia parameter is great enough to ensure relatively small deviations of particle motion from fluid.

This condition obtains when the square of an appropriate linear dimension (e.g., radius) of a particle equals or is less than $9\rho_0 \nu / 2\omega(\rho_1 - \rho_0)$, in which ρ_0 is the fluid density, ν the fluid kinematic viscosity, and ρ_1 the particle density. The author of reference 3 states: "For a water droplet in air fluctuating with a maximum frequency of sinusoidal component air motion of one cycle per second, the limiting radius of the droplet should be much less than 0.01 cm." In the present work, it is surmised that frequencies less than 1 cycle per second are the effective ones, for the most part. Nevertheless, while the density of jet fuel is about 0.8 of that of water, the difference is not great, and it must be recognized that accurate calculations would take into account the failure of liquid droplets to "follow" air motions perfectly. Clearly, this is extremely difficult to do in the absence of detailed information concerning turbulence power spectra at low altitudes.

The additional point might be made that the values of C^2 used in this report are based in part on observations of motions of particles which are neither of zero size nor in general of low (gaseous) density. Thus, any corrections that might be applied would have to take into account the fact that such observations do not yield the motions of the air itself.

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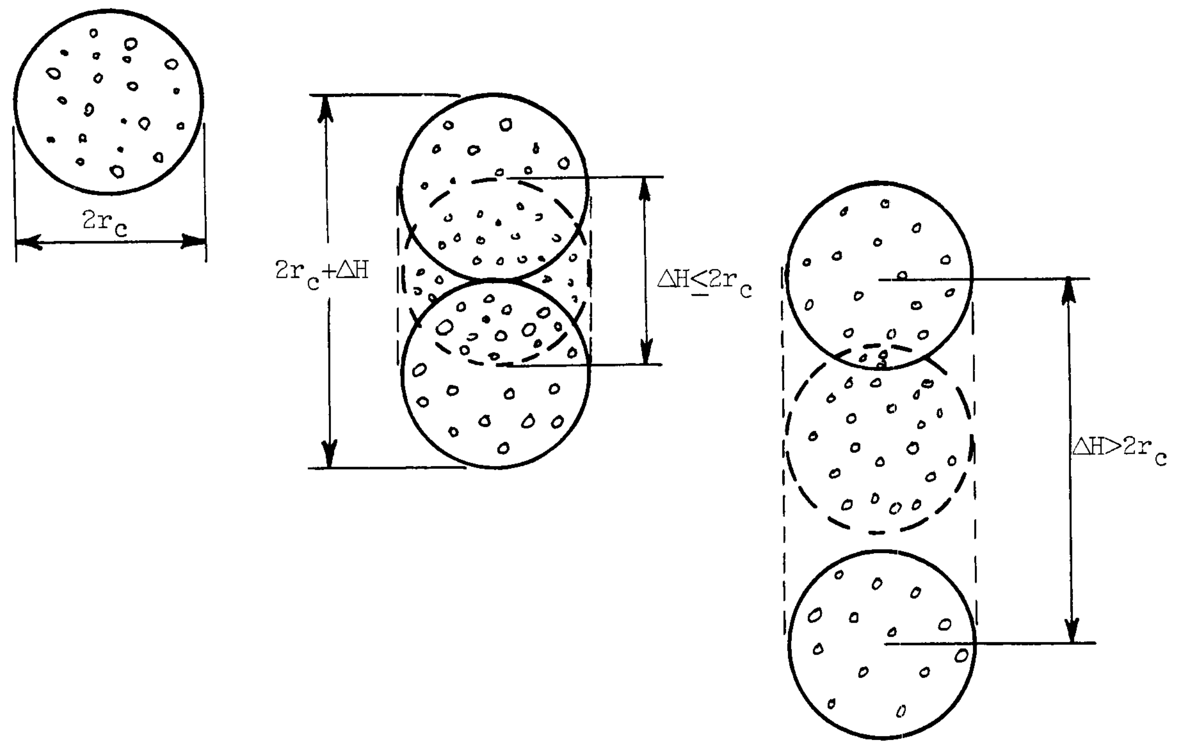

(a) Initial state.

(b) Condition after short time.

(c) Condition after sufficiently long time.

Figure 1. - Successive stages in fall of plume in absence of turbulent spreading.

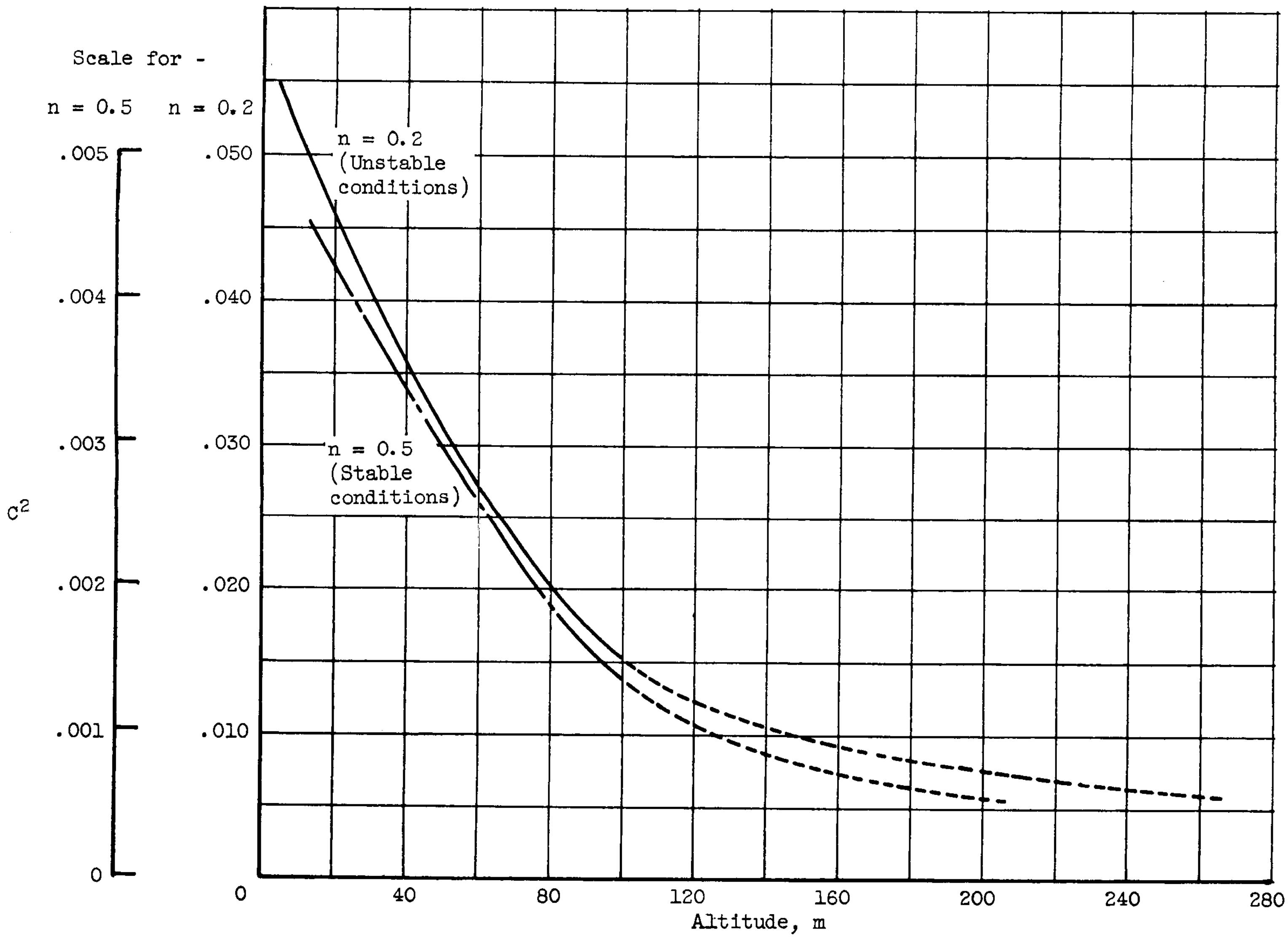

Figure 2. - Variation of diffusion coefficient C (ref. 2) with altitude.

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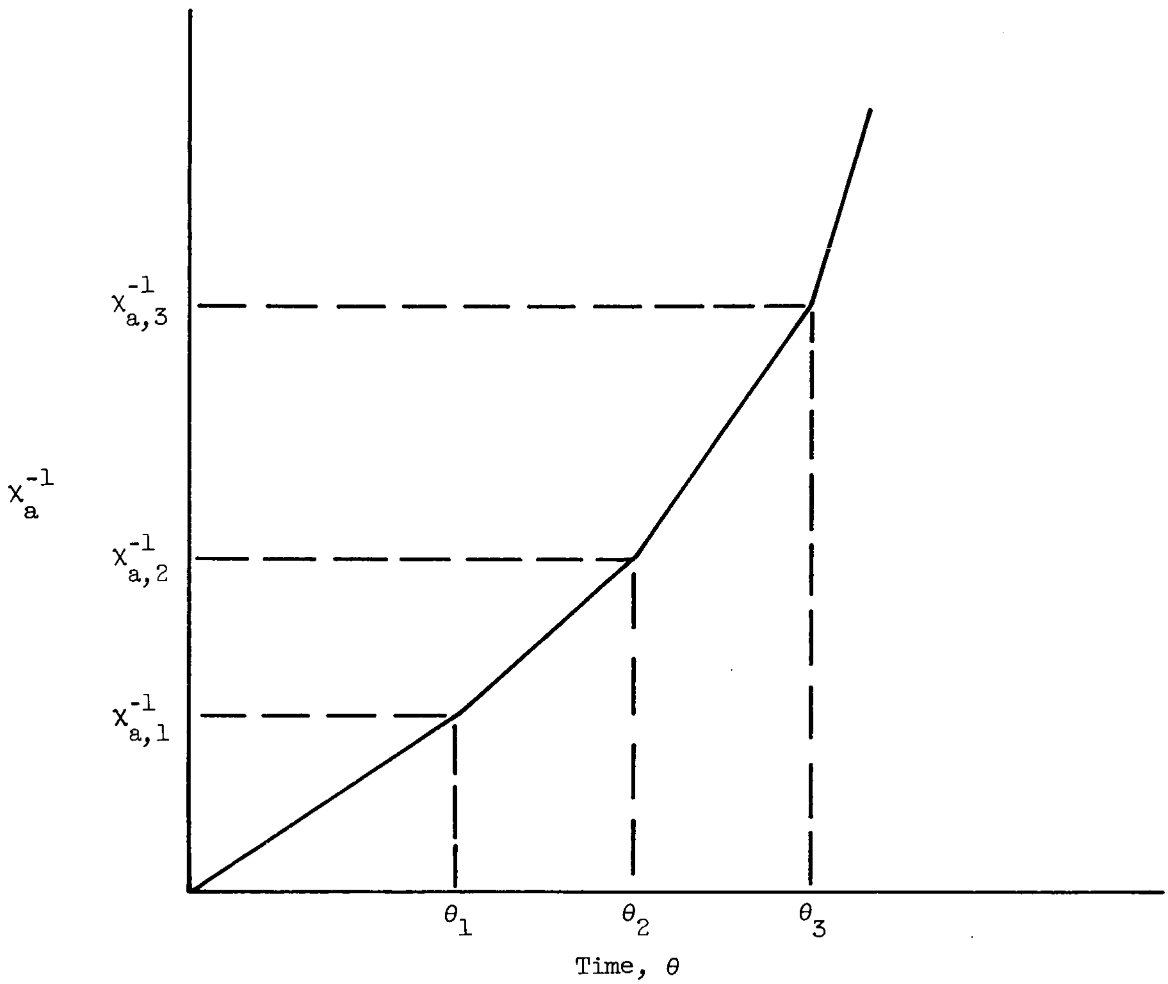

Figure 3. - Variation of mass concentration χ with time; calculations performed on step basis.

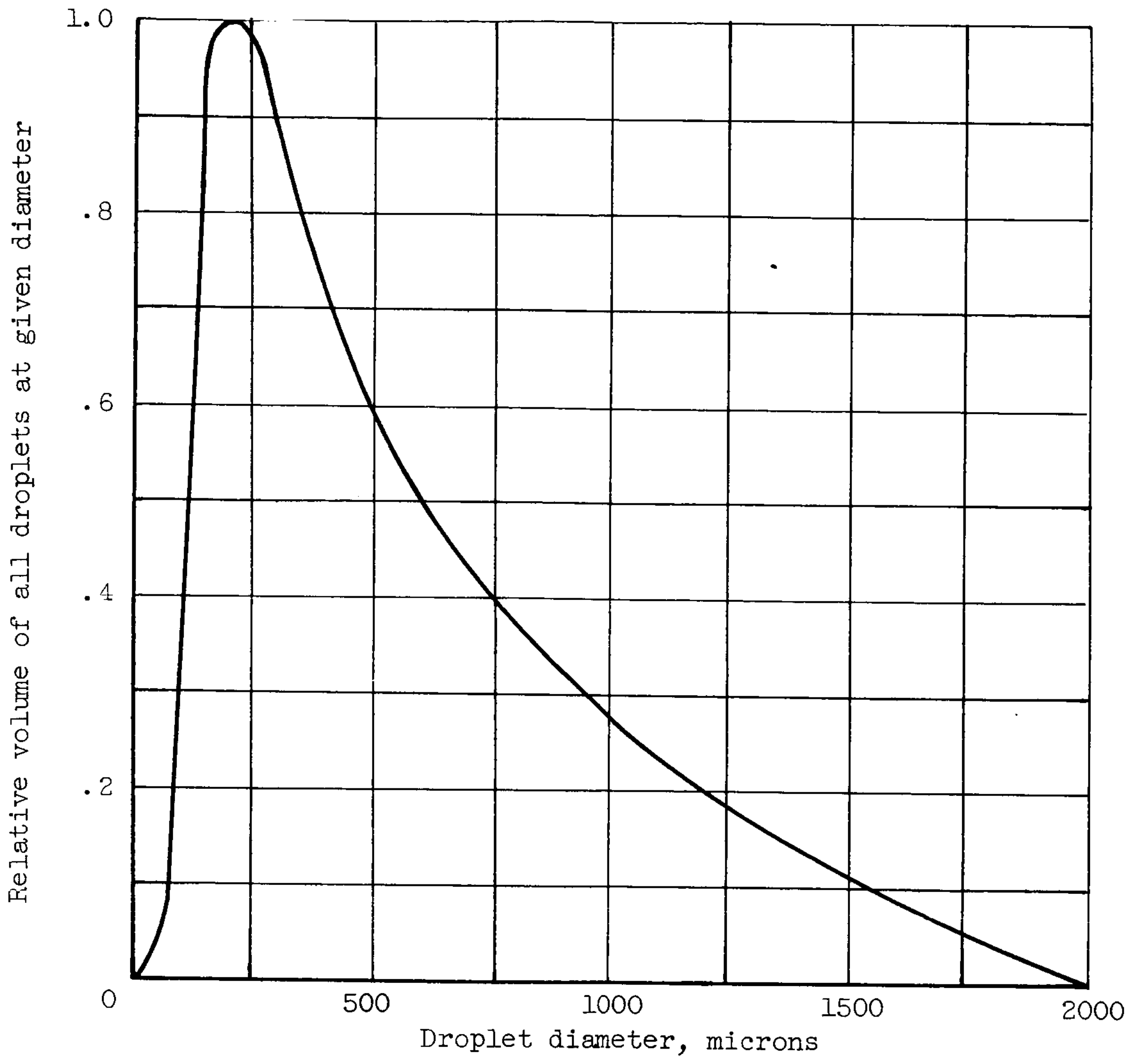

Figure 4. - Typical fuel droplet size distribution. Fuel, JP-4; airspeed during jettisoning, 250 knots.

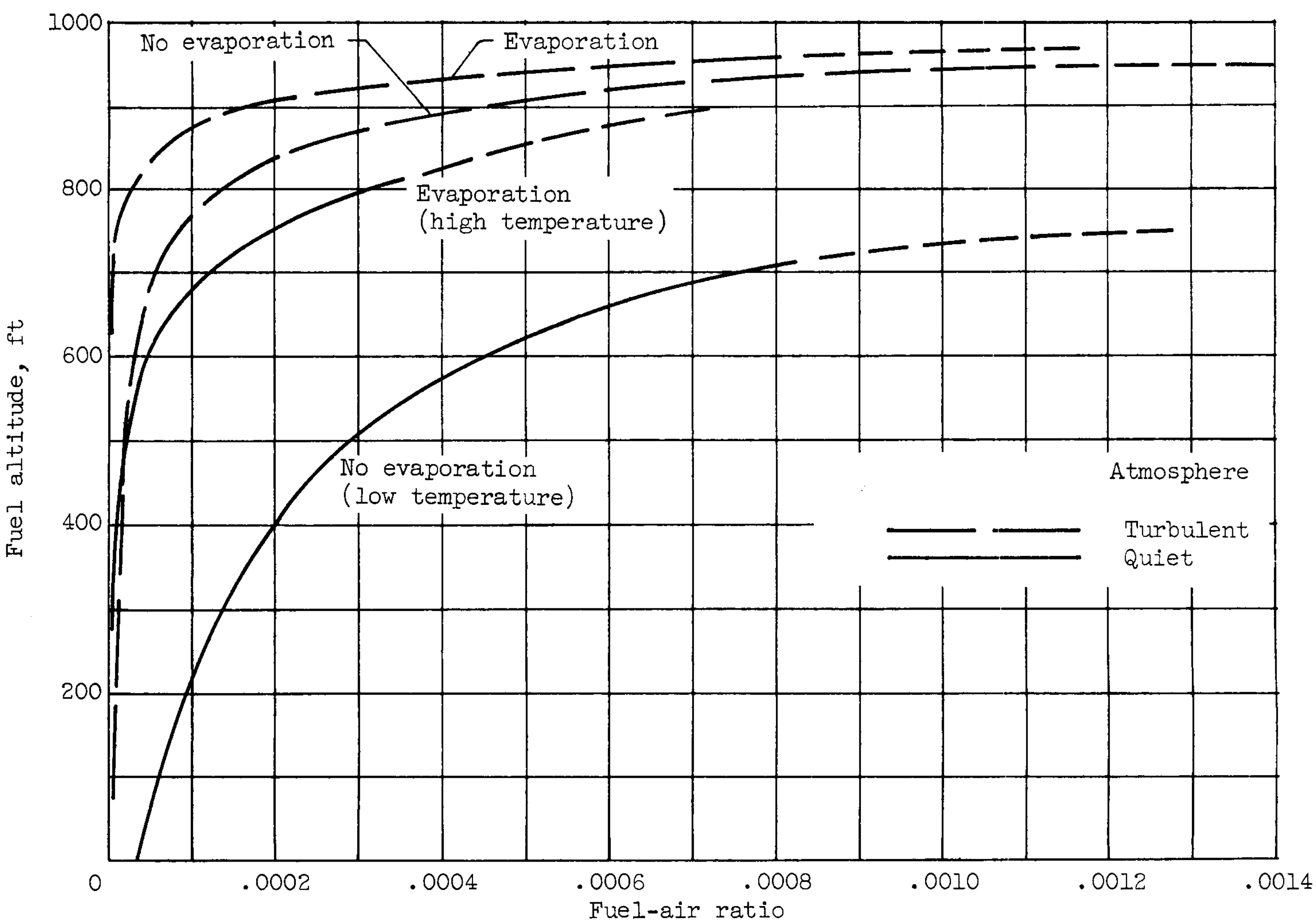

Figure 5. - Predicted fuel-air ratio as function of fuel altitude. Fuel, JP-4; jettisoning at 1000 feet at rate of 240 pounds per 1000 feet of aircraft travel.

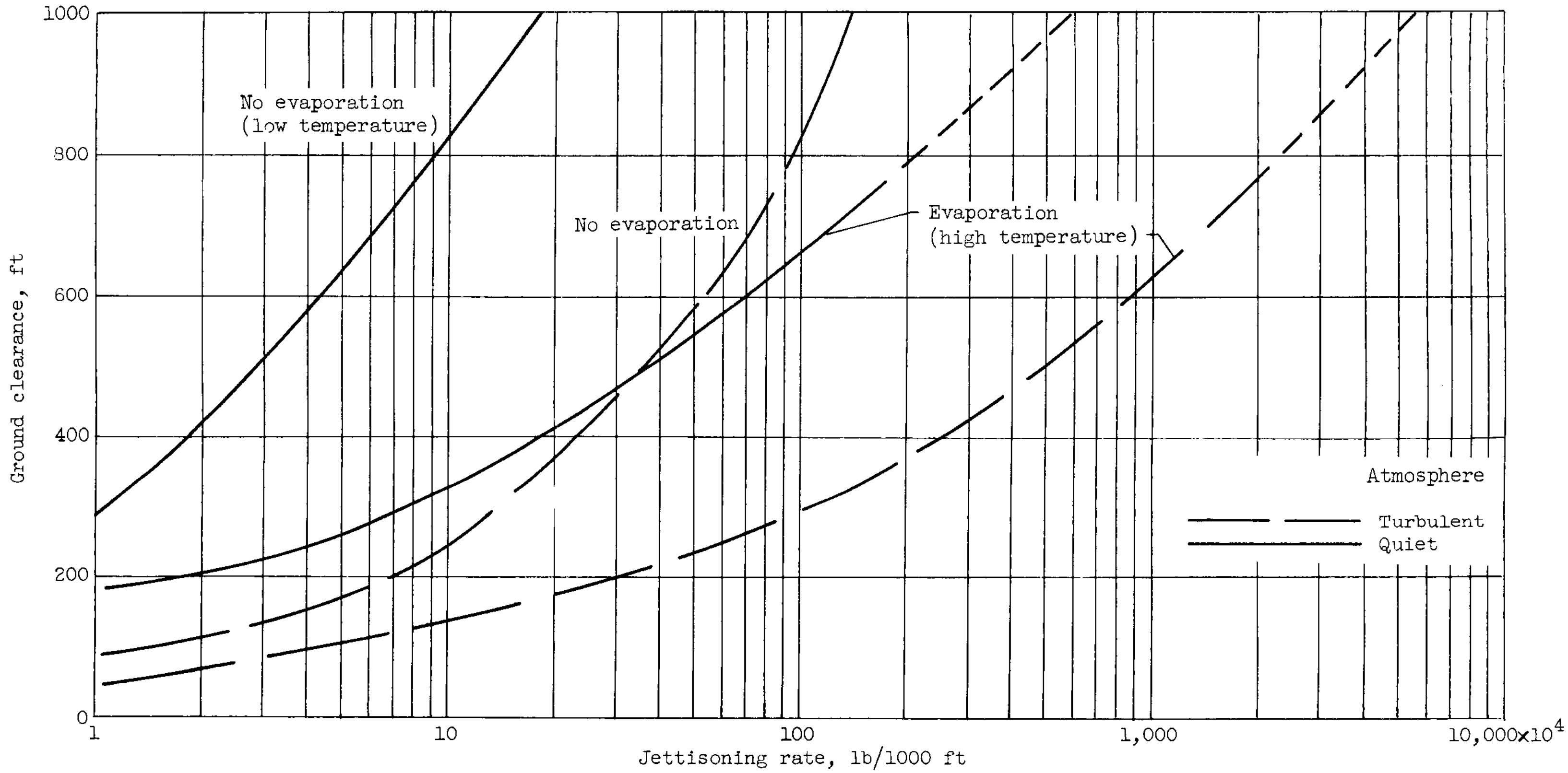

Figure 6. - Jettisoning rates productive of fuel-air ratio of 0.035 at ground level.